Low $Q^2$ structure functions
including longitudinal structure function

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on behalf of the H1 and ZEUS collaboration

Moriond QCD
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The world only e-p collider: HERA

A unique collider at DESY, Hamburg

2 collider experiments:
H1 & ZEUS

- proton beam
  (460, 575, 820,) 920 GeV
- electron/positron beam
  27.5 GeV

Center of mass energy
\[ \sqrt{s} = (225 \sim) 318 \text{GeV} \]

Operated since 1992 to 2007
2002-2007: HERA II
In total, each experiment gains
\~0.5 \text{ fb}^{-1}. 

Luminosity upgrade (2000-2002)
Deep Inelastic Scattering (DIS)

- Kinematic variables to describe DIS
  
  \[ Q^2: \] Virtuality
  \[ \rightarrow \text{probing power} \]
  \[ x: \text{Bjorken scaling variable} \]
  \[ \rightarrow \text{momentum fraction of struck quark} \]
  \[ y: \text{Inelasticity} \]
  \[ \sqrt{s}: \text{center of mass energy} \]

\[ Q^2 = sxy \]

\[ Q^2 = -q^2 = -(k - k')^2 \]

\[ x = \frac{Q^2}{2p \cdot q} \]

\[ y = \frac{p \cdot q}{p \cdot k} \]

- Inclusive DIS cross sections can be written with structure functions.

\[
\frac{d^2\sigma(e^+ p)}{dx dQ^2} = \frac{2\pi\alpha^2}{Q^4} Y_+ \left[ F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2) + \frac{Y}{Y_+} x F_3(x, Q^2) \right] \quad Y_+ = 1 \pm (1 - y^2)
\]

Cross section with point-like particle

Structure functions reflect momentum distribution of partons in the proton.
Structure functions and PDFs

Measured quantity: reduced cross section
\[ \tilde{\sigma}(e^\pm p) = \frac{Q^4Y_+}{2\pi\alpha^2} \frac{d^2\sigma}{dx dQ^2} = F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2) + \frac{Y}{Y_+} x F_3(x, Q^2) \]

Structure functions are used for determination of the parton distribution functions (PDFs), \( q(x, Q^2) \) and \( g(x, Q^2) \)

- **\( F_2 \)**: [Sea + valence] quarks, (gluon)
  \[ F_2 = \sum A_q x(q + \bar{q}) \frac{\partial F_2}{\partial \ln Q^2} \propto xg \]

- **\( F_L \)**: longitudinal structure function
  \( \rightarrow \) gluon (see later) sizable only at high \( y \)

- **\( xF_3 \)**: parity violation term (Electroweak)
  \[ xF_3 = \sum B_q x(q - \bar{q}) \] high \( Q^2 \) only (\( \rightarrow \) Next talk)
  \( \rightarrow \) Valence quarks

The \( Q^2 \) evolution can be described by perturbative QCD, using DGLAP equation.
HERA PDF from combined cross sections

- HERA I inclusive DIS cross sections from H1 and ZEUS are combined by averaging. (⇒Moriond QCD 2008, K. Korcsak-Gorzo)

Combination takes full account of systematic correlation.
⇒ Reduction of both statistical and systematic uncertainties.

- PDFs are determined by fitting these combined data sets.
  - 96-97 Low \(Q^2\) cross section
  - 94-00 High \(Q^2\) cross section

⇒ HERAPDF0.1
  - The measured cross section is well fitted in the large kinematic range.
  - Also succeeds to describe fixed target data.
Compared to previous fits from each experiment, H1 PDF 2000 and ZEUS-JETS PDF, the uncertainties are impressively reduced.
Further input for HERA PDF: The new $F_2$ results from H1 using HERA I data

- $F_2$ from the final $e^+p$ H1 cross section measurements at $12<Q^2<150$ GeV$^2$ from HERA I.

Combined result of
- Newly analyzed 2000 data ($E_p=920$ GeV)
- Reanalysis of 96/97 data ($E_p=820$ GeV)

Measured for $2\cdot10^{-4}<x<0.1$ ($y \leq 0.6$).

1.5~2% accuracy
Measurement of $F_L$
**\( F_L \): Longitudinal structure function**

- \( F_L \) is proportional to the cross section of longitudinal photon interacting with proton.
  \[
  F_L \propto \sigma_L
  \]
- In naïve QPM, proton has co-linear spin \( \frac{1}{2} \) quarks only.
  Longitudinal photon cannot interact with a quark. \( \rightarrow F_L = 0 \)
- gluon emission in the proton \( \rightarrow F_L > 0 \)
  i.e. \( F_L \) directly reflects gluon dynamics in the proton.

In pQCD:
\[
F_L = \frac{\alpha_s}{4\pi} x^2 \int_x^1 \frac{dz}{z^3} \left[ \frac{16}{3} F_2 + 8 \sum_q e_q^2 \left( 1 - \frac{x}{z} \right) z g(z) \right]
\]

\( \xrightarrow{\text{In PDF extraction in pQCD framework, gluon PDF is mainly determined from}} \)
\[
\frac{\partial F_2}{\partial \ln Q^2} \propto x g
\]

Measurement of \( F_L \) is a good test for the current understanding of proton structure and QCD.
Measurement of $F_L$

- Measured cross section is a combination of $F_2$ and $F_L$.

\[ \tilde{\sigma}(e^\pm p) = F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2) \]

\[ Y_+ = 1 + (1 - y^2) \]
\[ \rightarrow 1 < Y_+ < 2 \]

- Separation of $F_L$ from $F_2$.

Cross sections at the same $(x, Q^2)$ but the different $y$

\[ y = \frac{Q^2}{sx} \rightarrow \text{multiple beam energies} \]

HERA was successfully operated with low $E_p$ for the last months. Data sets with three different energy are available.

\[ \sqrt{s} = 318, 252, 225 \text{ GeV} \quad (E_p = 920, 575, 460 \text{ GeV}) \]

First direct $F_L$ measurements at low $x$ ($x \sim 10^{-3}$) = gluon dominance.

- Extraction of structure functions without QCD assumption
- Consistency check of pQCD framework for the proton structure.
**Strategy for the measurement**

- High $y$ cross section measurement should be done.
- One of the difficulties is identification of scattered positron $e'$ with low energy and low angle.
  → Large background due to mis-ID.

Estimation of background

- **H1**: using wrong charge distribution.
- **ZEUS**: using MC, checked by BG events detected by a tagger

- **H1 $F_L$**
  
  12 ≤ $Q^2$ ≤ 90 GeV$^2$  
  35 ≤ $Q^2$ ≤ 800 GeV$^2$  

- **ZEUS $F_2$ & $F_L$**
  
  24 ≤ $Q^2$ ≤ 110 GeV$^2$  

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*PLB655 (2008) 139 (preliminary)*
Reduced cross sections (ZEUS)

- Reduced cross sections at three beam energies. Offset is added for each beam energy.

- Compared to ZEUS-JETS predictions.

- The data tends to flatter at lowest x (=highest y) region and deviates from $F_L=0$.
  $\Rightarrow F_L$ contribution

H1 reduced cross sections are on extra slides.
$F_L$ (H1)

$F_L$ for $12 \leq Q^2 \leq 800$ GeV$^2$

- Non-zero $F_L$ is supported.
- pQCD prediction using H1 PDF 2000 is consistent with measured $F_L$. 
ZEUS $F_2$ and $F_L$

- $F_2$ and $F_L$ are extracted from reduced cross sections without QCD assumptions.

- Non-zero $F_L$, $0 < F_L < F_2$, is supported.

- Compared to ZEUS-JETS PDF predictions.

→ pQCD predictions are consistent with the measurement.
x-averaged $F_L$

- Averaged $F_L$ for each $Q^2$, extracted at given $x$.

- Compared to predictions with different
  - PDFs
  - pQCD frameworks

- Not sensitive to the differences of the predictions, but consistent with them.

- Extension to low $Q^2$ is ongoing.
$R$ from ZEUS

$$R = \frac{F_L}{F_2 - F_L}$$

- $R$ extracted for each $Q^2$ at given $x$.
- Various predictions are consistent with measurement.
- Overall value of $R$:

$$R = 0.18^{+0.07}_{-0.05}$$
Summary

*ep* scattering at HERA gives precise understanding of the proton structure.

Further understanding is still coming.

- Significantly improved determination of PDFs using H1/ZEUS combined cross sections of HERA I.
- Direct measurement of $F_L$.
  - $F_L$ is separated from $F_2$ without QCD assumption.
  - pQCD predictions are consistent with measured $F_L$. 
Summary

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HERA PDFs have impact on LHC.  

A.M. Cooper-Sarker at HERA-LHC 2008

Further improvement may come...
Extra slides
**H1 reduced cross sections**

- No offset.
- Measured for wider $Q^2$ range. $12 \leq Q^2 \leq 90 \text{ GeV}^2$ and $35 \leq Q^2 \leq 800 \text{ GeV}^2$
- Compared to predictions using H1 PDF 2000.
- $F_L$ contribution is seen as turnover.
Details of HERA PDF slide from DIS08 A.M. Cooper-Sarker

Chosen form of the PDF parametrization at $Q_0^2$

$$xf(x) = Ax^B(1-x)^C(1 + Dx + Ex^2 + Fx^3...)$$

The number of parameters for each parton has been optimized.

Optimization means starting with only BLUE parameters and adding D, E, F parameters until there is no further $\chi^2$ advantage.

PDFs fitted: gluon, $u$, $d$, $u_{bar}=u_{bar}+c_{bar}$, $D_{bar}=d_{bar}+s_{bar}+b_{bar}$

Sea flavour break-up at $Q_0$: $s = fs*D$, $c = fc*U$, $AU_{bar}=(1-fs)/(1-fc)AD_{bar}$

$fs = 0.33D (s=0.5d)$, $fc = 0.15U$ consistent with dynamical generation

$mc=1.4$ GeV mass of charm quark $mb=4.75$ GeV mass of beauty quark

Zero-mass variable flavour number heavy quark scheme (for now)

$Q_0^2 = 4$ GeV$^2$ input scale $Q^2_{min} = 3.5$ GeV$^2$ minimum $Q^2$ of input data

$\alpha_s(Mz) = 0.1176$ PDG2006 value